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ROCK COAST INHERITANCE: AN EXAMPLE FROM GALICIA, NORTHWESTERN SPAIN

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ABSTRACT

A shore platform on the western coast of Galicia in northwestern Spain has been inherited from interglacial stages when sea level was similar to today. The wide, gently sloping intertidal platform is backed in places by supratidal rock ledges, and in other places by a steeper and narrower supratidal ramp. The gradient of the intertidal platform is consistent with the relationship between platform gradient and tidal range, but the slope of the ramp is much too high. The abandoned and degraded sea cliff is grass-covered along most of this coast, and the ledges and the ramp, which extend up to several metres above the highest tides, are covered by lichen and, in places, by salt-tolerant plants. Radiocarbon-dated sediments in the cliff, which range up to 36 000 years in age, lie on top of an ancient beach deposit. The former beach, remnants of which are found *in situ* on the ramp and rock ledges, as well as two caves that are filled with the dated sediments, are probably last interglacial in age. The morphological and sedimentary evidence suggests that the supratidal ramp and ledges were also formed during the last interglacial stage, whereas the wider intertidal platform is probably the product of several older interglacials, when sea level was generally similar to today. A general model is proposed for the inheritance of shore platforms in macro- and microtidal environments. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: rock coasts; Spain; interglacial sea levels; inheritance; shore platforms; Schmidt Hammer R-values

INTRODUCTION

The palaeosea-level record suggests that marine processes may be slowly modifying shore platforms and cliffs that were formed in the Pleistocene, during interglacial periods of high sea level (Trenhaile, 1987, in press a). Shore platforms in resistant rocks often appear to be too wide to attribute to contemporary marine erosion, and they are often backed by rock ledges and raised beaches which testify to the effect of sea levels that were several metres higher than today. These platforms are frequently in front of high cliffs with composite profiles that suggest that they are also ancient features that are being modified slowly by marine and subaerial processes. In the Channel Islands, southern Wales and southern Australia, amino-acid analysis and uranium series dating have shown that some sea caves are at least last interglacial in age (Goede *et al.*, 1979; Davies, 1983). Nevertheless, it is usually difficult to determine whether, or to what degree, rock coasts are inherited from the past. The lack of sediments has generally prevented direct dating of rock coast features, and the morphological evidence is often ambiguous.

There is generally little evidence on rock coasts of sea levels that were similar to today, especially where present rates of erosion would have been sufficient to have removed till covers, ancient beach deposits and structural remnants which may once have existed. It is now sometimes possible to estimate the age of shore platforms and other rock surfaces, however, using a variety of exposure-dating techniques (Brooke *et al.*, 1994; Stone *et al.*, 1996). In southern Australia, for example, U/Th dating of ferruginous and calcareous crusts, and thermoluminescent dating of associated sediments suggest that a subhorizontal intertidal platform developed in the last interglacial when sea level was higher than today. The platform was then buried under

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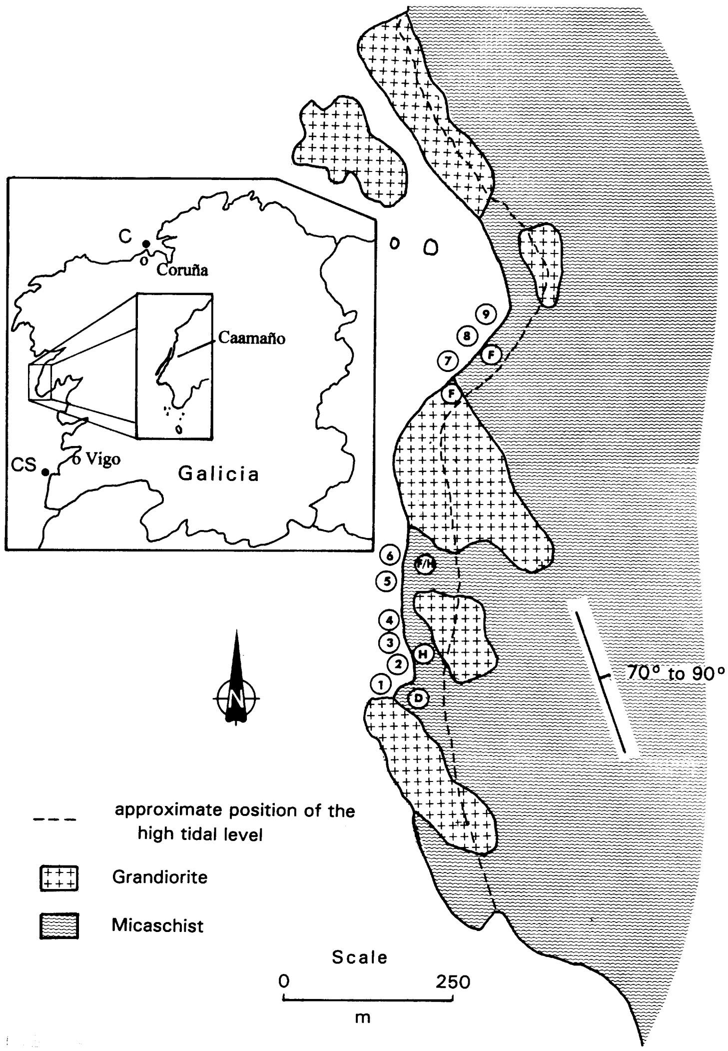


Figure 1. The study area. Circled numbers refer to the surveyed profiles and the circled letters to the rock strike-dip class (see text for a description of the classes). Profiles 1 to 4 are in the southern bay, 5 and 6 are in the middle bay and 7 to 9 are in the northern bay. CS and C on the inset map refer to the wave buoys off Cape Silleiro and Coruña, respectively

soil in the last glacial stage, when sea level was much lower, and exhumed and partly modified by waves in the Holocene. Sloping rock ramps in this region, which extend up to more than 10 m above present sea level, are probably polygenic, having developed under rising and falling sea level during the Cenozoic Era (Bryant *et al.*, 1990; Young and Bryant, 1993).

Although the potential role of inheritance in areas of less resistant rock is particularly contentious, in the absence of compelling evidence to the contrary, most workers have concluded that shore platforms in fairly weak rocks are postglacial features (Hills, 1971; Gill, 1972; Sunamura, 1973; Takahashi, 1977; Kirk, 1977). This study, however, has identified morphological and sedimentological evidence for the inheritance of shore platforms in fairly weak rocks along a short but varied section of the coast near Caamaño, on the southern shore of the Ria de Muros y Noia in Galicia, in northwestern Spain (Figures 1 and 2).

Figure 2. The intertidal platform and supratidal ramp in the southern bay looking towards the south

THE CAAMAÑO COAST

Galicia occupies the northwestern section of the Hercynian Hesperic or Iberian Massif. Three main lithological units can be distinguished: granites and granitic rocks, which dominate in the western region; basic and ultrabasic rocks in a small section in the northwest; and shales, schists, gneiss, quartzites and other metamorphic rocks which are particularly extensive in central and eastern Galicia. These rocks were strongly fragmented during the latter phases of the Hercynian orogeny (Parga Peinador, 1969), producing an extensive network of faults running northwest–southeast and northeast–southwest. Later, during the early Mesozoic, a group of north–south running fractures developed as a result of rifting in the Atlantic. Uplifted blocks and basins were formed by intense tectonic movements along the unstable Atlantic margin from the Eocene until at least the early Quaternary (Pérez Alberti, 1991). Tropical conditions during the Tertiary, which became progressively less humid during the later stages of this period, resulted in deep weathering of the rocks and sediments in the tectonic depressions and along the coast (Nonn, 1966; Pérez Alberti, 1991, 1993). Glacial and periglacial processes were important during the Pleistocene (Pérez Alberti *et al.*, 1994; Pérez Alberti and Valcárcel Díaz, 1998). There were two well-defined cold climatic periods during the Weichselian glacial stage. The first, around 30 000 to 35 000 years ago, was more humid. Glaciers descended to at least 600 m above sea level, and periglacial deposits, which were affected by frost creep and gelifluction, accumulated down to sea level. The second cold period, about 18 000 years ago, was colder and drier, and resulted in the formation of widespread deposits containing frost-shattered clasts, and the development of rock glaciers and blockfields throughout the region.

Global circulation models suggest that the winter limit of permanent pack ice was as far south as northern Spain about 18 000 years ago. Because of lower sea level, however, the main effect of glacial-stage climates on contemporary rock coasts was subaerial rather than marine. Therefore, while shorelines were being subjected to tidally induced frost action and erosion by sea ice during glacial stages, the abandoned interglacial shore platforms and cliffs at higher elevations were experiencing less severe and less frequent frost action associated with atmospheric changes in temperature, and periglacial mass movements (Trenhaile, 1987, 1997).

The western coast of Galicia consists of a succession of flat surfaces, tilted and descending in altitude to the east, strongly fractured and deeply weathered rocks that have facilitated marine erosion (Pérez Alberti *et al.*, 1997) and periglacial deposits that cover the slopes. The Caamaño coast is situated along the zone of contact between Precambrian to Silurian grandiorites and metamorphic rocks. The metamorphic strata are steeply dipping (75 to 90°), generally towards the land, and they strike between 145° and 165°. Granitic dykes, mainly consisting of aplites, cross the shore platform in several places. The dykes developed at higher temperatures than the metamorphic rocks and, being in greater disequilibrium with present conditions, they weather more rapidly. Intensely weathered granitic dykes have therefore been differentially eroded and they form deep troughs and low basins on the shore platform, which generally consists of moderately weathered micaschists. Visual observation and Schmidt Rock Test Hammer measurements suggest that there is little difference in the degree of weathering on the upper and lower portions of the platform surface (Figure 3). This implies that rather than shallow surface weathering occurring during the Pleistocene as cliff retreat progressively exposed the shore platform to marine and subaerial conditions, deep subaerial weathering, up to several metres below the surface, took place under warm, wet conditions during the Tertiary. This conclusion, which is consistent with the occurrence of deep, chemically weathered rock profiles throughout Galicia, suggests that fairly rapid marine erosion of the previously weathered rocks in the cliff and shore platform may have occurred during the Quaternary.

The Caamaño coast is a meso-tidal, swell wave environment, which is near to the transitional zone between the storm wave environment of northwestern Europe and the west coast swell environment at lower latitudes (Davies, 1972). Although wave energy levels in swell-dominated areas are generally lower than in storm wave environments, they are fairly high on the Caamaño coast because of the short distance of travel of the waves from the generating areas. Swell waves approach the Caamaño coast most often from the north-northwest, and less frequently from the west and southwest. Wind velocity is generally greater in winter, and most of the largest waves (height >3m) are generated at this time to the north of the Iberian Peninsula, by depressions moving northwestwards. The tides along this coast are semidiurnal, with a mean spring tidal range of 2·2 m (Table I).

Coastal sediments

Although the intertidal zone at Caamaño is occupied by an extensive and largely bare shore platform, the cliffs are covered in places by sedimentary deposits. The thickest sediments accumulated in a former valley in the middle portion of the northern bay. In other parts of Galicia, coastal sediments are largely derived from mountains that are very close to the coast, but at Caamaño there is a coastal plain, or rasa, several kilometres in width, between the mountains and the coast. The sediments at Caamaño are therefore more local in origin. A total of 114 samples were collected from a vertical trench, almost 8 m high, which was excavated along the full height of the cliff in the sediments at the back of the bay. The samples were subjected to textural, mineralogical, thin section micromorphological, pollen, and C and N isotopic analyses, and the pH in water, potassium chloride, phosphorus, organic carbon and nitrogen contents, base exchange and exchangeable aluminium were also determined. In addition, eight organic-rich samples were radiocarbon dated (Figure 4) (Costa Casais *et al.*, 1994, 1996).

Six main horizons were distinguished, consisting of supratidal organic material (levels 6A and 4), frost-shattered clasts (levels 5C and 3C), alluvial sediments (level 2) and colluvial slope deposits (level 1), ranging up to 36 000 years in age (Figure 4). There are no deposits from the early and much of the middle Weichselian glacial stage in the study area. As these older coastal deposits have been identified elsewhere in Galicia (Ramil Rego and Fernández Rodriguez, 1995), it is possible that strong stream flow at Caamaño prevented their deposition, or subsequently removed them, on the floor of the former valley.

At the base of the sedimentary column, aeolian sediments lie beneath a weakly evolved soil, or Atlantic ranker (level 6A), in which the main processes were bioturbation and the accumulation of organic matter. This deposit formed between 36 000 and 32 000 years ago. The next layer in the column (5C) consists of stony colluvial material, with clasts lacking any preferred orientation, and varying from a few centimetres to a metre or more in size. These deposits appear to have developed under cold, humid periglacial conditions between about 32 000 and 30 000 years ago. Level 4, which is similar to level 6, formed under interstadial

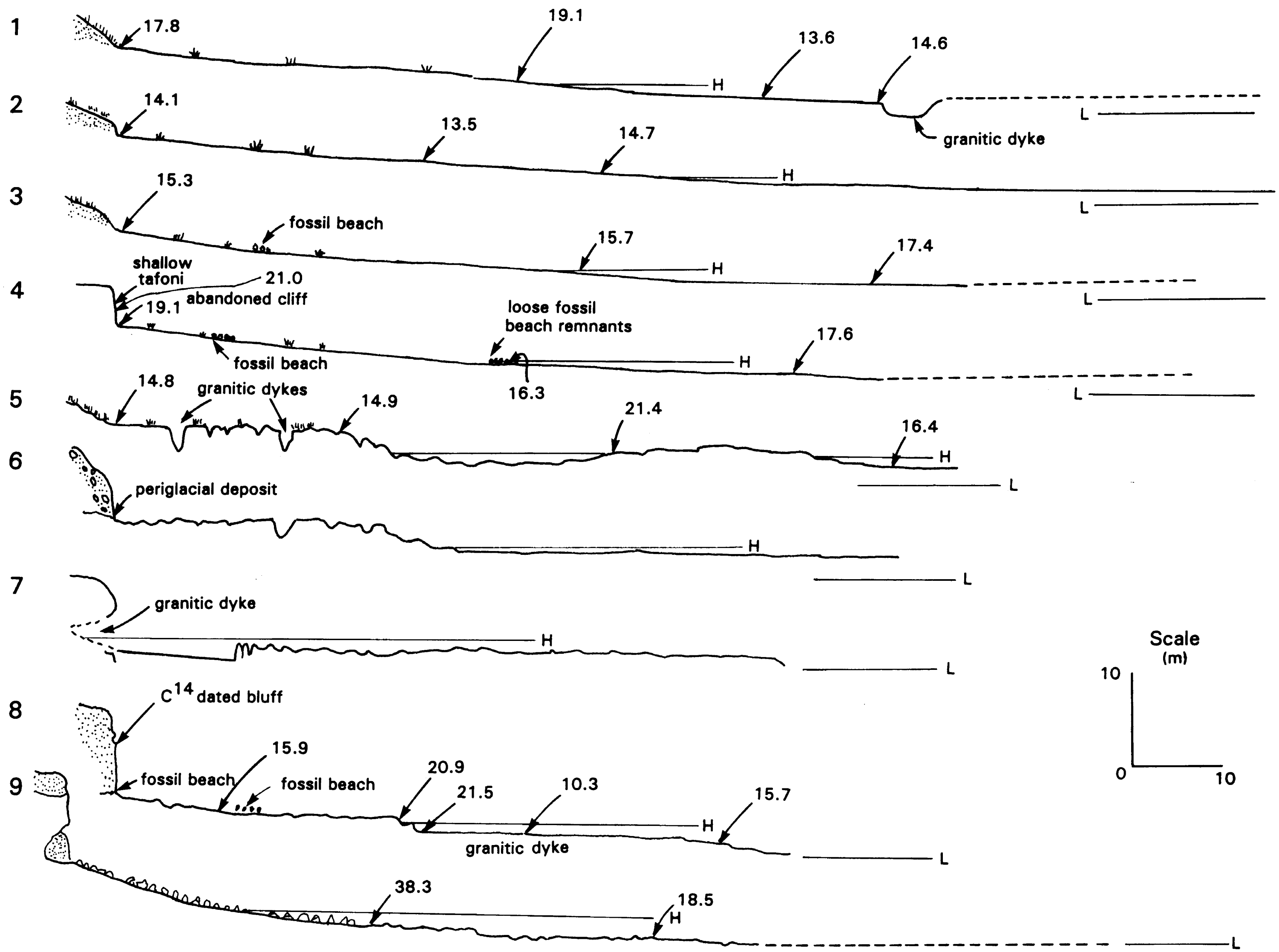
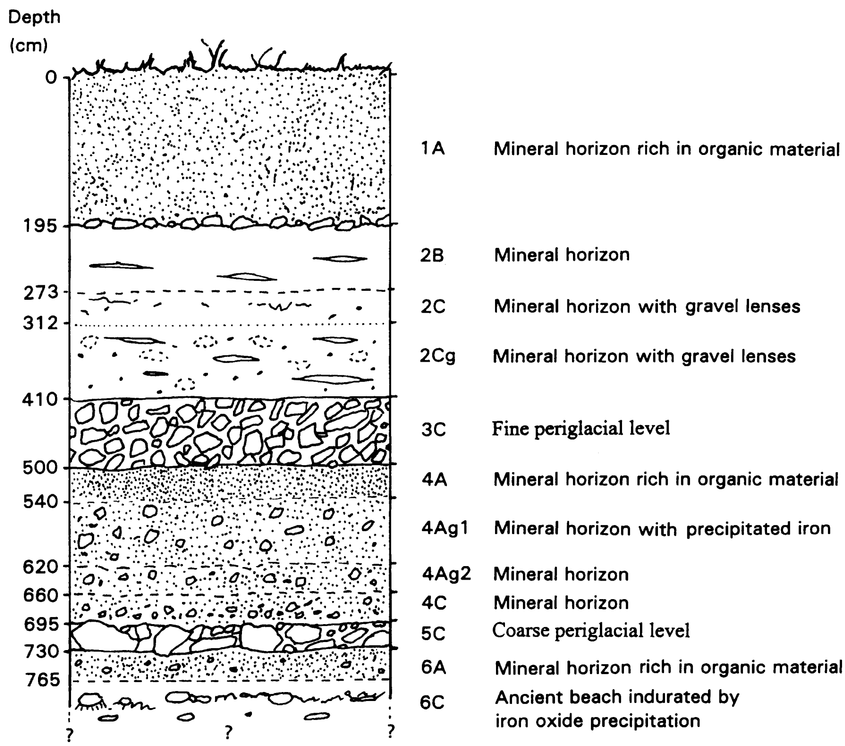


Figure 3. Surveyed shore platform profiles and mean Schmidt Rock Test Hammer R-values (arrowed numbers). H refers to the height of the highest high tides and L to the lowest low tides. Dashed extensions of the platform were under water during the study period and could not be surveyed

Table I. Non-directional significant wave heights for Cape Silleiro and Coruña (Dirección General de Puertos del Estado–http://www.puertos.es/boyas/animaboya.html)

Height (m)	<0·5	1	1·5	2	2·5	3	3·5	4	4·5	5	>5
% per year CS	1·82	20·3	25·8	17·7	12·3	8·8	5·7	3·09	1·76	1·16	1·17
% per year C	1·54	20·72	25·12	18·06	12·33	8·55	5·5	3·5	1·9	1·16	1·53

CS, Cape Silleiro (near Vigo) 42° 05·8’ N, 08° 55·8’W (data collected from a buoy in water 75 m deep from 22/02/91 to 12/12/96)
C, Coruña 43° 24·8’N, 08° 23·0’ W (data collected from a buoy in water 50 m deep from 14/07/82 to 30/11/96)



Radiocarbon data

Lab.	Date	Depth
GrN-20506	36050 + 1430 -1210 BP	750-755 cm
GrN-21591	32340 + 2400-1800 BP	740-745 cm
GrN-20507	30120 + 670-620 BP	655-660 cm
GrN-21592	29400 + 2200-1700 BP	610-615 cm
GrN-21593	28750 + 1100-900 BP	515-520 cm
GrN-20508	20160 ± 270 BP	500 cm
GrN-22280	2720 ± 140 BP	160 cm
GrN-22279	530 ± 80 BP	100 cm

Figure 4. Sample cliff section and tabulated radiocarbon dates in the northern bay

Figure 5. A remnant of the ancient beach located about 10 m from the cliff foot on profile 4. The lighter toned material at the bottom of the photograph is modern beach sediment

conditions between 30 000 and 20 000 years ago. Level 3C consists of angular clasts, mainly granite, without any preferred orientation, in a matrix of finer material. This layer was deposited during a colder and drier colluvial–periglacial pulsation, which began about 20 000 years ago. Level 2 contains rounded, fluvially deposited sand grains (fluvisols) that were formed under wetter and less cold conditions from about 18 000 to 12 000–11 000 years ago. A thin line of stones at the top of this level (below 1A) represents colluvial slope deposits formed during a third cold phase in the Dryas, about 11 000 years ago. Level 1 is a cumulic soil formed in the Holocene by the incorporation, through colluvial processes, of discrete additions of eroded and previously pedogenized material. Measurements of ^{13}C and ^{15}N in the organic-rich silt–clay fractions have allowed three main episodes of sedimentation and post-depositional pedogenesis to be identified.

The sedimentary column lies on top of an ancient stony beach deposit with a hardened crust cemented by precipitated iron oxides (level 6C). The deposit consists largely of small, rounded stones, up to a few centimetres in diameter, in a matrix of coarse-grained sand–material which is similar to modern beach sediments at the cliff foot (Figure 5). Although it was too old to be radiocarbon dated, the sedimentary position and elevation of the former beach, which is approximately 2·8 m above the level of the highest high tides, suggests that it is last interglacial in age. There are also a few small, isolated remnants of this former beach, including in places some larger, angular cobbles between 10 and 20 cm in diameter, on the upper portion of the shore platform and ramp. These remnants are up to about 25 m from the cliff base in the northern and southern bays. If it can be assumed that the beach remnants were oxidized under sediments similar to those at the rear of the northern bay today, then these sediments must have extended much further

seawards during the last glacial stage. Although the ancient beach may have been extensively eroded, the occurrence of only isolated pockets of loose gravel and coarse sand at the back of the platform today, suggests that the beach was unlikely to have been very extensive along this coast during the last interglacial stage.

The shore platform

A theodolite was used to survey the shore platform along nine profiles extending from the cliff foot to the low tidal level. Two bench marks, located at either end of the study region, were used to relate platform elevations to tidal levels. Schmidt Rock Test Hammer measurements were also made at 24 sites located at quasi-regular intervals along surveyed profiles 1 to 5 and 8 and 9; 30 measurements were made at each site. Rock hammer measurements were not made along profiles 6 and 7 because of the difficulty of obtaining representative values for serrated platform surfaces consisting of steeply dipping strata of variable resistance to erosion. The rocks in the platform are moderately to severely weathered, and most test hammer R-values fell between 10 and 25, the lower values generally corresponding to severely weathered granitic dykes. With the exception of troughs and the lower portion of some platform profiles which have been cut along dykes, variations in rock hardness did not account for the occurrence of ramps, raised ledges or other anomalous morphological elements on the shore platform (Figure 3).

There are marked differences in the morphology of the shore platform in the three bays (Figure 3). In the most southern bay, the platform has a fairly smooth surface and the profiles consist of a lower subhorizontal platform and a higher, sloping ramp (Figure 2). The ramp does not appear to be structurally controlled. It occurs in steeply dipping strata that strike almost perpendicular to the shoreline in the southern portion of the bay and almost parallel to the shore in the north. Profiles 1, 2 and 3 are backed by a largely uneroded and grass-covered slope. Although the sediments in this slope have not been analysed, they appear to consist of *in situ* layers of shell, and dune and beach sand, together with coarse sand and gravel which may have been carried down the slope by flows. Profile 4 is backed by a cliff of weathered rock with honeycombs and small tafoni on its upper face. The steepness of this cliff is not a product of contemporary marine erosion, however, but the result of weathering and the release of rock flakes along planes of schistosity that are parallel to the cliff face. The platform in the middle bay consists of an irregular, supratidal rock ledge which truncates the steeply dipping rock strata. The ledge is deeply dissected along weak, very weathered granitic dykes, and it is followed seawards by a lower, less irregular intertidal platform (Figure 3, profiles 5 and 6). The degraded, inactive rock and sediment cliff consists of stony periglacial deposits, and it is covered in vegetation. The very irregular surface of the shore platform between the middle and northern bays largely reflects differences in the degree of weathering. Elevated areas largely consist of less weathered granite, whereas the lower sections correspond to very weathered and weak grandiorite, which contains a higher proportion of more easily weathered plagioclase feldspar minerals. A cave at the back of profile 7 has developed in moderately weathered micaschists along a very weathered granitic dyke. The irregular metamorphic rock platform in the northern bay consists of a low ledge dissected along granitic dykes which also form the lower, intertidal platform surface. The cliff behind profile 8 is composed of the radiocarbon-dated sediments which have been described previously. The platform along profile 9 is in hard, unweathered quartzites and, although it is irregular, it lacks the high ledge at the rear of profile 8. The dated sediments fill two caves which have been cut along steeply dipping bedding planes into the base of the weathered rock cliff at the rear of profile 9 (Figure 6). The floors of these caves are about 3·5 m above the highest level of the tides (Figure 3), and they are only being re-excavated slowly by storm wave spray and splash during periods of exceptionally high sea level; they are therefore probably at least last interglacial in age.

It has been suggested that the width of shore platforms in bedded rocks is partly determined by the strike and dip, which affect the accessibility of cliffs and the surface of shore platforms to waves (Everard *et al.*, 1964). Trenhaile (1987) distinguished eight combinations of strike and dip, which were ranked, in alphabetical order, according to their susceptibility to erosion (class A being the most susceptible and H the least). This model helped to account for variations in the width of shore platforms in several areas (Trenhaile, in press b). Assuming that waves approach the shore approximately normally, the structural classes encountered by the incoming waves change with variations in coastal orientation. Therefore, although rock dip and strike were essentially constant in the study area, there were some changes in structural class, relative

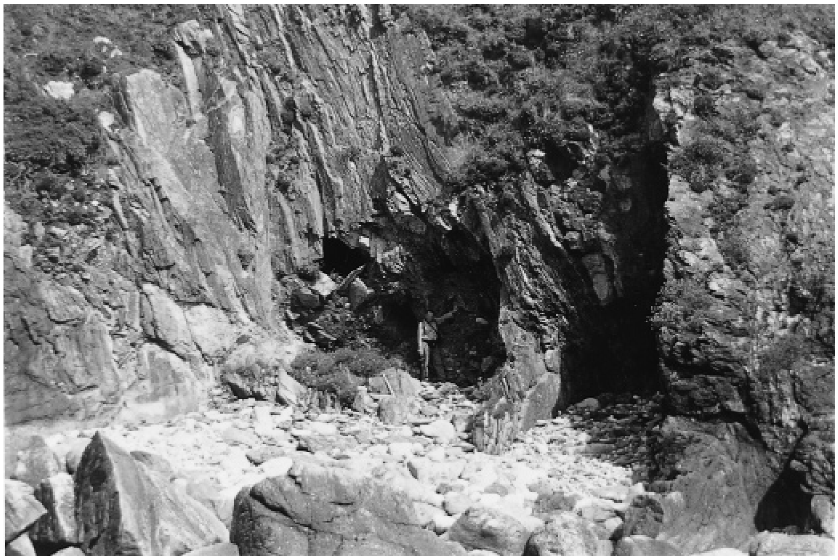


Figure 6. Two sediment-filled, inherited caves at the back of profile 9

to wave approach, along the coast. There was, however, little correspondence between rock structure and platform width, defined as extending from the cliff foot to the level of the lowest low tides (Figure 1). For example, the widest and smoothest platform is in the southern bay (profiles 1 to 4), where the dip is almost vertical and the strike is subparallel to the coast (class H), whereas the narrowest platforms are in the northern bay where the vertically bedded rocks strike obliquely to the cliff (class F). Furthermore, variations in platform morphology cannot be attributed to differences in rock hardness, as determined by the Schmidt Rock Test Hammer (Figure 3). There appear to be two main reasons for the occurrence of a ledge in the middle bay and a smooth ramp in the southern bay. Firstly, the strata are usually thicker (5 to 15 cm) and therefore more resistant in the upper portion of the middle bay than on the ramp in the southern bay (bed thickness is generally from 1 to 3 cm). Secondly, sand and fine gravel have been able to accumulate on the upper part of the ramp in the southern bay, possibly because it is more deeply indented than the middle bay. The ramp has a smooth, even surface which strongly suggests that this is the only part of the study area where abrasion has played an important role.

With the exception of profile 7, which is cut into a very weathered granitic dyke at the cliff foot, most profiles extend up to several metres above the highest high tides (Figure 7). Lichen and clumps of vegetation, mainly *Armeria maritima* and *Crithmum maritimum*, with *Eryngium maritimum* in small pockets of fine gravel or aeolian sand, grow in the three bays on the ledges and on the upper parts of the ramp, above the level of the highest tides and up to about 25 m from the inactive cliff base. There are small remnants of the raised beach on the ramp in the southern bay, and on the rock ledge on profile 8 in the northern bay. Furthermore, whereas the gradient of all the profiles below the highest high tidal level is very low (0·3 to 0·8°), and consistent with the contemporary tidal range, the ramps in the southern bay have gradients of 4 to 5°, which are much greater than one would expect according to the present tidal range (Trenhaile, 1997). There is therefore considerable evidence of platform inheritance from a period of higher sea level along this coast, which, according to the elevation of the cliff–platform junctions and the cave floors, was from 3 to 3·5 m above its present level in this part of northwestern Spain. This figure is consistent with widespread evidence of higher sea level during the last interglacial (Trenhaile 1987), and it suggests that this area has been stable since that time.

Regression analysis, based on hundreds of surveyed profiles from a variety of coastal environments (Trenhaile, 1997, in press b), suggests that there is a moderately strong correlation ($r^2 = 0{\cdot}69$) between the

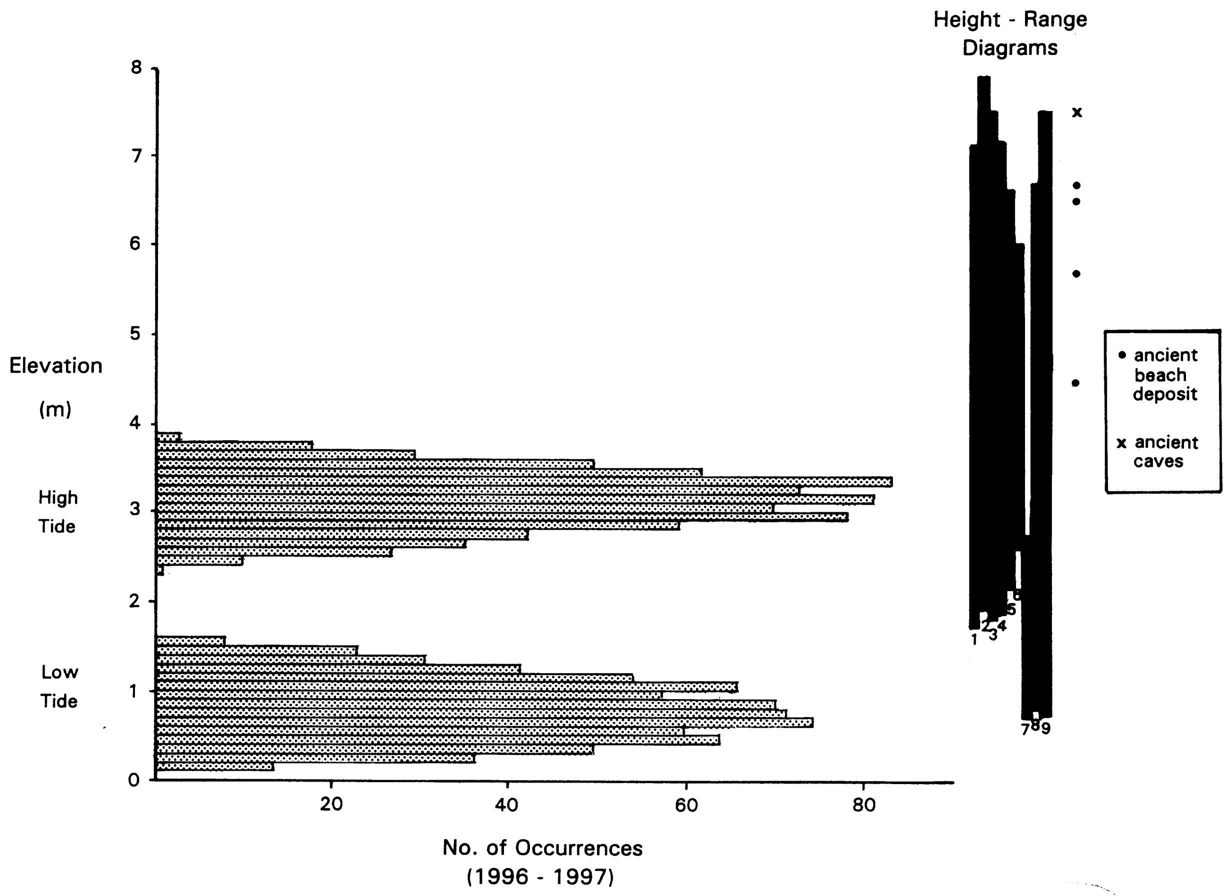


Figure 7. The elevational range of each surveyed profile, and the elevation of the ancient beach deposits and caves at Caamaño superimposed on a plot of the frequency of elevations of high and low tides in 1996 and 1997. The numbers beneath the height-range diagram refer to the surveyed profiles. The base of the height-range diagrams represents the lowest points that were surveyed

mean regional platform gradient of shore platforms (β) and mean spring tidal range (T_r), and that:

$$\beta = 0 \cdot 26\,T_r \tag{1}$$

where β is in degrees and T_r is in metres. Assuming that the spring tidal range was similar to today's during the last interglacial (2·2 m), it follows that the maximum width of the ramp should be about 220 m. The width of the ramp, defined as extending from the cliff foot to the break of slope at the rear of the shore platform, is between 45 and 70 m. This suggests that the ramp was in the early stages of development and did not attain equilibrium during the few thousand years of higher sea level at the peak of the last interglacial (isotopic substage 5e).

Waves and platform morphology

Wave energy rapidly declines in the surf zone in proportion to the distance travelled from the breakpoint. The mean critical ratio (γ) between breaker wave height and depth is about 0·78, although it varies according

Table II. Wave steepness (H_b/L_o) for breaker types on the intertidal shore platform and ramp at Caamaño

Type of breaker	Platform (0·5°)	Ramp (4·5°)
Surging	$\leq 1{\cdot}90 \times 10^{-5}$	$\leq 1{\cdot}55 \times 10^{-3}$
Plunging	$1{\cdot}90 \times 10^{-5}$ to $4{\cdot}76 \times 10^{-4}$	$1{\cdot}55 \times 10^{-3}$ to $3{\cdot}88 \times 10^{-2}$
Spilling	$\geq 4{\cdot}76 \times 10^{-4}$	$\geq 3{\cdot}88 \times 10^{-2}$

to the slope of the bottom. Collins (1970) found that waves break when:

$$\gamma = 0{\cdot}72 + 5{\cdot}6 \tan \beta \tag{2}$$

where β is the gradient of the bottom. This equation indicates that waves between 0·5 and 1 m in height break between about 75 and 150 m from the water's edge over the gently sloping shore platform (average gradient about 0·5°) at Caamaño. Smaller waves, which break closer to shore, probably lack the energy to accomplish much erosion.

Morison *et al.* (1954) and Miller *et al.* (1974) found that the greatest pressures are exerted by the bores of plunging breakers, followed in turn by the bores of spilling breakers, plunging breakers, spilling breakers and finally by near-breaking waves. There have been several attempts to quantify the relationship between breaker type, bottom slope and wave properties (Trenhaile, 1997). The breaking equivalent of the surf similarity parameter (ξ_b) is also known as the Iribarren number:

$$\xi_b = \frac{\tan \beta}{(H_b/L_o)^{0{\cdot}5}} \tag{3}$$

where H_b is the breaker height and L_o is wavelength in deep water. Battjes (1974) determined that surging or collapsing breakers occur when $\xi_b > 2$; plunging breakers when $0{\cdot}4 < \xi_b < 2$; and spilling breakers when $\xi_b < 0{\cdot}4$. The Iribarren number was used to calculate the range of wave steepnesses required to generate each type of breaker on the ramp (gradient about 4·5°) and shore platform at Caamaño (Table II). The results suggest that if breaker heights are between 0·1 and 1 m and wavelengths between 5 and 100 m, spilling breakers will dominate on the intertidal platform and plunging breakers on the ramp. These conclusions are consistent with field observations that spilling breakers occur on the intertidal platform and plunging breakers where waves impinge on the lower part of the ramp.

Although abrasion may occur occasionally on the upper ramp at Caamaño, where some coarse sand and gravel has accumulated at the cliff foot, the most important mechanical wave erosional processes on the platform and lower ramp are probably water hammer and air compression in joints and other crevices. These processes operate at the water surface and their efficacy is therefore determined by the pressures exerted by the bores of broken waves. The ramp experiences the bores of plunging breakers, which exert more pressure than the bores of the spilling breakers on the platform, and, as they break fairly close to shore, they retain more of their energy. Nevertheless, because of its elevation, most of the ramp is reached by wave uprush only during occasional storms. Consequently, erosion appears to be quite slow on the lower portion of the ramp, and it is negligible on the upper ramp. Slow contemporary modification of the wide, gently sloping shore platform can be attributed to wave attenuation, wide surf and swash zones, the dominance of spilling breakers and bores and wave saturation in the inner, bore-like surf zone, where wave height is locally depth controlled and largely independent of the height outside the breaker zone (Thornton and Kim, 1993). Further evidence for slow contemporary rates of erosion on the shore platform is provided by the lack of freshly quarried rock surfaces and debris, the presence of molluscs, including *Patella* spp., *Mytilus edulis* and *Littorina* spp., and the crustacean *Balanus perforatus*, over much of its surface, and echinoderms and *Lithophyllum incristans* and other algae on the inner walls of potholes. The probable existence of similar wave and tidal conditions in

the past may help to explain why the shore platform has been able to persist, and therefore be repeatedly inherited, from previous interglacial stages.

A PLATFORM INHERITANCE MODEL

Although there are some important differences between the oxygen isotopic records obtained from deep-sea cores, a comparison of 11 of the most detailed records suggested that sea level was lower than today in interglacial stages 7, 13, 15, 17 and 19, and similar to today in stages 5e, 9 and 11 (Shackleton, 1987). Although it is unlikely that eustatic sea level has been more than a few metres higher than at present during the last 2·5 million years, there is considerable evidence to suggest that it was several metres higher than today during the last interglacial stage (Broecker *et al.*, 1968; Chappell, 1983).

To simplify the following discussion for modelling purposes, it is assumed that sea level and tidal range in the penultimate interglacial (stage 7) were similar to today's (stage 1). To consider the effect of higher sea level during the last interglacial (stage 5), it is necessary to distinguish between several possible situations.

(a) In microtidal areas (0 to 2 m tidal range), there was no overlap between the range of elevations affected by mechanical wave erosion in stage 5 and the range during stages 7 and 1. The platform formed during stage 7 would therefore have been entirely subtidal during stage 5, and, being much less susceptible to erosion, it would have been essentially fossilized (Figure 8a, b, c and d).
(b) In macrotidal (tidal range greater than 4 m) and possibly mesotidal regions (tidal range from 2 to 4 m) there was a degree of overlap between zones of effective wave erosion during isotopic stage 5 and stages 7 and 1. Part of the platform from stage 7 would therefore have continued to be modified during stage 5 by wave quarrying, abrasion and other processes that only operate, or are most active, near the water surface (Figure 8e, f and g) (Trenhaile, 1987).
(c) High rates of erosion, resulting from weak rocks and strong waves, would have allowed platforms to attain equilibrium gradients and widths during interglacial stages.
(d) Low erosion rates would not have allowed equilibrium to be attained.

If sea level at Caamaño had been 3 to 3·5 m higher than today during the last interglacial, the low tidal level during stage 5 would have been about 1 m higher than the high tidal level in stages 7 and 1. Because of the effects of wave uprush at the high tidal level and abrasion below the low tidal level, however, the range of elevations within which mechanical wave erosion is effective is somewhat greater than the tidal range. Therefore, it is likely that the upper portion of the zone of effective wave erosion at Caamaño during stage 7 and today was just within the lower portion of the wave erosional zone during stage 5.

Low tidal range

A platform would have been cut into the cliff several metres above the cliff–platform junction during the last interglacial. A sloping ramp would have developed under slow erosional conditions (Figure 8a and b), and a platform with a gentle equilibrium gradient, commensurate with the low tidal range, if erosion had been more rapid (Figure 8c and d). During the Holocene, sea level rose to its present position, a level which, for modelling purposes, is assumed to have been broadly similar to that in stage 7 and in other, older interglacials. Platforms and ramps would have been reduced to narrower ledges by marine erosion in areas with slow Holocene erosion, but they would not have been completely removed. Most of the intertidal shore platform would have been inherited, though slightly lowered, from the penultimate interglacial, with the exception of the upper portion which had been cut into the base of the ledge, and an equal portion trimmed back at the low tidal level (Figure 8a and c). This explanation may account for the subhorizontal or gently sloping high tidal ledges of Australasia (Trenhaile, 1980, 1987; Sunamura, 1992), which could have developed during the last interglacial or during the period of higher sea level in the middle Holocene. If contemporary marine erosion had been faster, all the last interglacial ledge could have been removed. The lower portion of the intertidal platform would therefore have been inherited, though modified, but not the upper part (Figure 8b and d). This

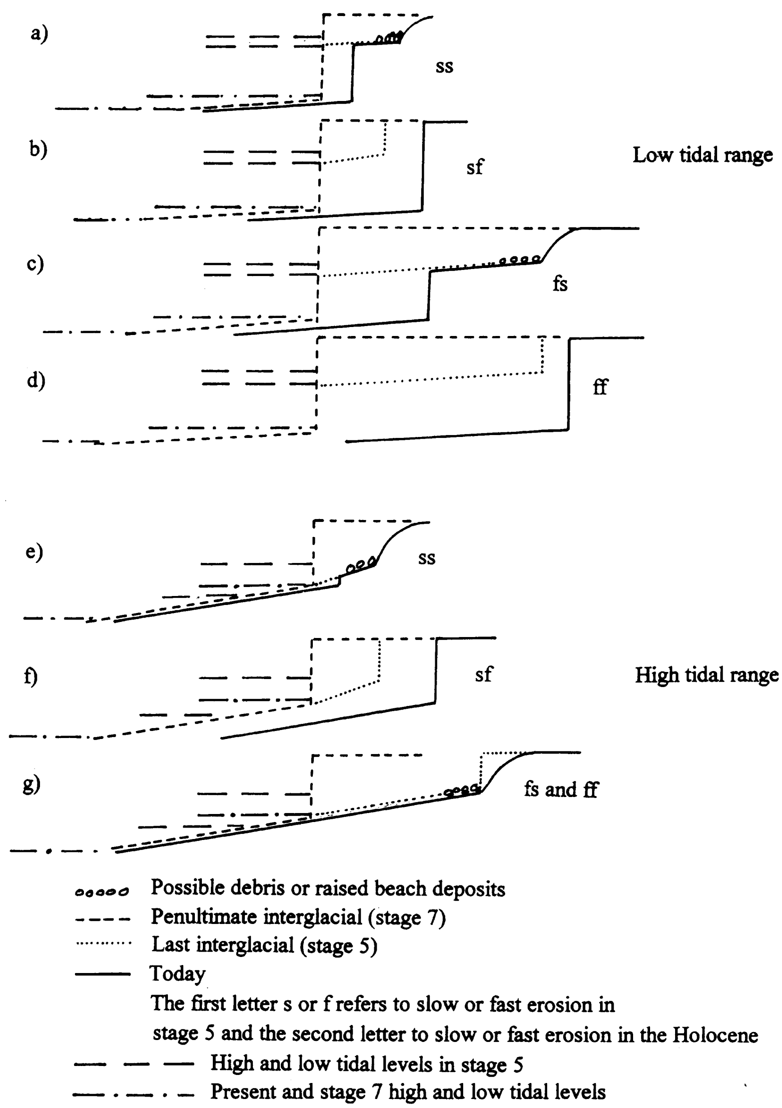


Figure 8. A model of platform inheritance. For convenience, tidal range is used to determine whether there was any overlap between the zone of effective wave action in stage 5 and the zone in stages 7 and 1

situation may account for the subhorizontal platforms in weak metamorphic and sedimentary rocks in Gaspé, Québec, western Newfoundland and southern Australia (Trenhaile 1987).

High tidal range

If part of the upper portion of the penultimate interglacial platform had been within the intertidal zone during the period of higher sea level during the last interglacial, it would have been extended up to the new cliff–platform junction, located at about the high tidal level during stage 5. A sloping ramp would had been produced at the cliff base if erosion had been slow during stage 5 (Figure 8e and f). Continued slow erosion during the Holocene would then have formed a small cliff at the seaward end of the ramp. Almost all the intertidal platform would have been inherited, apart from sections of equal width at the high and low tidal

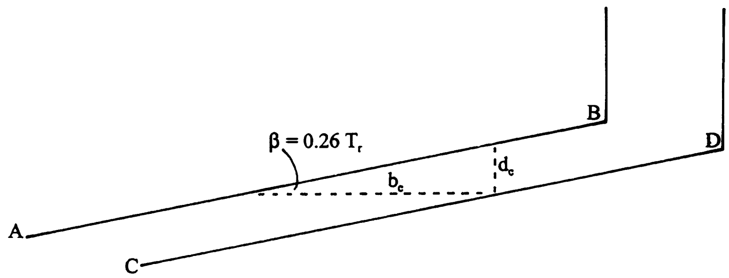


Figure 9. Platform downcutting (d_c) and backcutting (b_c) of an inherited platform (AB) of the same width and gradient (β) as the contemporary platform (CD)

levels (Figure 8e). Possible examples of this situation are found on the resistant Cambrian grit and slate coast of the Isle of Man in western Britain (Phillips, 1970), and in the middle bay of the Caamaño coast of western Galicia. Alternatively, fast erosion would have completely removed the ramp. The intertidal platform would then have been inherited, though modified, except for areas near the high and low tidal levels (Figure 8f). In the latter situation, exemplified by the Liassic limestone and shale coast of the Vale of Glamorgan in southern Wales (Trenhaile, 1972), fairly rapid erosion may have removed any sedimentological and morphological evidence which may once have existed of the former higher sea level, making it difficult to demonstrate whether any of the contemporary platform surface has been inherited.

Rapid erosion during stage 5 would have extended the equilibrium slope landwards. During the Holocene, irrespective of slow or fast erosion, lower sea level would then have simply reoccupied the lower portion of the platform. The modern intertidal platform would therefore have been inherited from stage 7 and possibly from earlier interglacials, while the upper portion would have been inherited from the last interglacial (Figure 8g). This situation appears to account for platform profiles in the southern bay at Caamaño, although the significantly higher gradient of the ramp suggests that either tidal range was higher during stage 5, or that there was not enough time for the platform to attain an equilibrium gradient.

Platform downcutting and backcutting

There is no accepted definition of the term ‘inheritance’, and it can therefore mean different things to different people. Few workers would consider that inheritance had occurred if the low tidal shoreline at the time that the sea first reached its present level in the Holocene, was located landward of the position of the cliff base during the last interglacial (Trenhaile, 1989). The term could be applied to all other situations where the early Holocene shoreline was seaward of the position of the interglacial cliff base. Simple inheritance, whereby the sea reoccupied an ancient surface without any modification, is unlikely to have occurred, however, particularly as sea level was several metres higher than today in the last interglacial. The question therefore arises as to the degree of Holocene downcutting, backwearing and other modification of ancient surfaces that can occur before platforms are no longer considered to be inherited. For example, is a platform inherited if it developed through the reduction of an older, last interglacial surface that was several metres higher, or should we consider it to be a contemporary platform cut, by rising sea level, into a low cliff?

Assuming that platform gradient (in degrees) is equal to about 0·26 times the mean spring tidal range (Equation 1), and that tidal range and therefore equilibrium platform gradient in the last interglacial stage were similar to today, it can be shown that (Figure 9):

$$d_c = b_c \tan 0{\cdot}26\, T_r \qquad (4)$$

where d_c is the amount by which the platform inherited from the last interglacial had to be lowered to attain equilibrium platform gradient and width in the Holocene for a given amount of backcutting (b_c). This

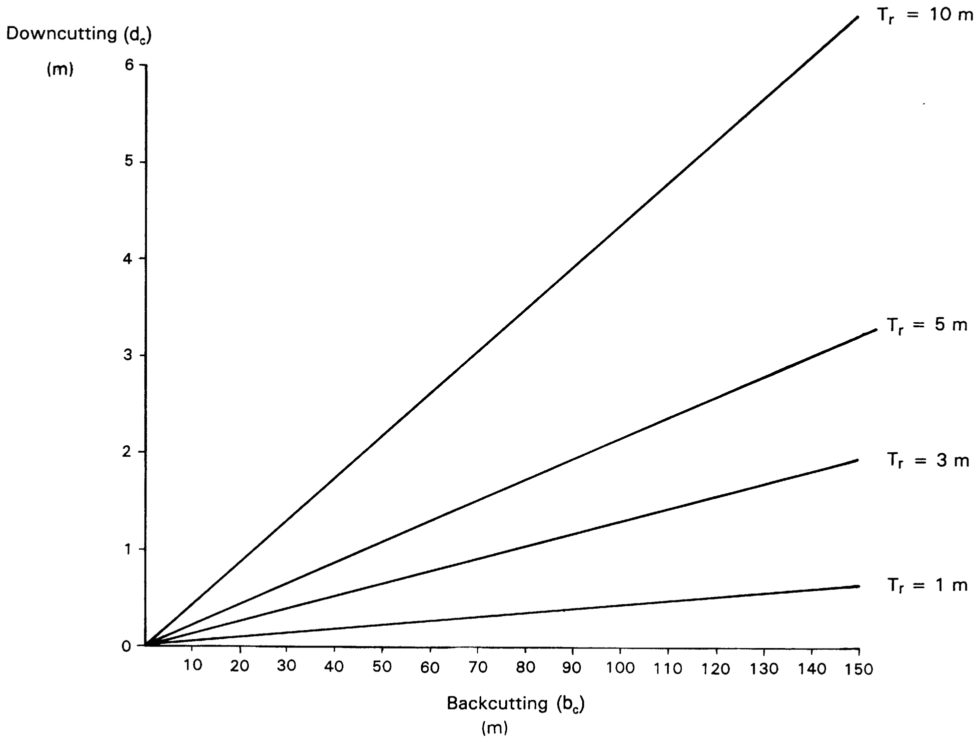


Figure 10. Amounts of Holocene platform downcutting (d_c) by which platforms inherited from the penultimate interglacial had to be lowered to attain equilibrium platform gradients and widths for a given amount of backcutting (b_c)

equation was used to calculate d_c for variable amounts of backcutting, for a variety of tidal ranges (Figure 10). The results suggest that there is a linear increase in the amount of downcutting with the tidal range and the degree of backcutting. Therefore, if one considers a platform to be inherited only if there has been slight modification, then inheritance can only have occurred in microtidal areas, or in macrotidal environments where there has been little backcutting (up to 10–20 cm) during the Holocene. For a platform with a linear profile:

$$W = T_r / \tan\beta \tag{5}$$

where β is platform gradient, and W is equilibrium platform width. Substituting for β from Equation 1 produces:

$$W = T_r / \tan(0{\cdot}26T_r) = T_r \cot(0{\cdot}26T_r) \tag{6}$$

Equation 6 suggests that maximum platform width is approximately 220 m in all tidal environments. This is similar to the width of the platforms in the southern bay at Caamaño. Nevertheless, although maximum platform width may therefore be independent of tidal range, there is actually a wide variation in width according to such factors as rock hardness, wave energy, cliff height and the mobility of the cliff foot deposits (Trenhaile, in press b). The maximum width concept is consistent with the attenuation of wave energy over wide, gently sloping shore platforms, which limits the size of the waves reaching the cliff foot. This eventually produces a balance between the rates of erosion at the high and low tidal levels (Trenhaile, 1987; Sunamura, 1992).

CONCLUSIONS

Inheritance is difficult to demonstrate where shore platforms are in equilibrium with the present level of the sea. At Caamaño, for example, if Holocene rates of erosion had been fast enough to remove the ramp and the ancient beach remnants, there would be little reason to suggest that the intertidal shore platform was other than entirely contemporary. The evidence at Caamaño for platform inheritance includes:

(a) the occurrence of lichen and plants on the higher portion of the platform and ramp;
(b) degraded and abandoned coastal cliffs in the southern and middle bays;
(c) cliff–platform junctions and cave floors that are well above the elevation of the highest tides;
(d) remnants of an ancient beach on the upper part of the shore platform and ramp in the southern and northern bays;
(e) caves filled with ancient sediment in the northern bay;
(f) ramp gradients in the southern bay that are too high for the tidal range;
(g) the occurrence of an elevated, non-structural ledge in the middle bay; and
(h) dated Weichselian-age sediments above an ancient beach in the northern bay.

Both the upper and lower portions of the platform are inherited in the southern bay. The ramp was cut during the period of higher sea level during the last interglacial, when, assuming that the tidal range was similar to today, there was insufficient time to attain a low, equilibrium profile. The wide, gently sloping intertidal platform, which is seaward and therefore more ancient than the ramp, has probably been cut over several interglacial stages when sea level was similar to today. This portion of the platform is in equilibrium with today's sea level and tidal range, and there appears to be little erosion taking place at the present level of the sea. Although we should continue to exercise restraint in ascribing wide shore platforms in fairly erodible rocks to inheritance, the results of this work provide support for the contention that, although the evidence is often lacking, many wide, intertidal platforms may have been formed during previous interglacial stages when sea level was similar to today.

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